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Modeling the effect of storage temperature on the respiration rate and texture of fresh cut pineapple

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ABSTRACT

The effect of temperature on the respiration rate and texture of fresh cut pineapple was studied over the course of 10 days of storage. The thermal exchange between the pineapple trays and the cooling environment was simulated using the finite element method and tested at 6 °C. The temperatures on pineapple wedges differed between the cold point and points near the surface, indicating that the respiration rate may be affected in pineapple subjected to temperature abuse. The experimental respiration rates obtained were used to develop a model relating respiration to O_2 and CO_2 concentrations at different temperatures using the closed system method. The O_2 consumption and CO_2 production of pineapple wedges was accurately modeled using Michaelis–Menten kinetics. The texture degradation of pineapple wedges follows a zero-order kinetic reaction at different temperatures and the thermal dependence of the model's parameters for both respiration rate and texture degradation was described by Arrhenius-type equations.

1. Introduction

In recent years, considerable effort has been made to ensure the quality and safety of minimally processed fruits until they are consumed. Controlling product temperature during refrigerated storage is of critical importance: an optimum temperature maintains the visual quality of fresh cut fruits and reduces their respiration rate, tissue softening and microbial spoilage (Cantwell and Suslow, 2002). A break in the cold chain can lead to a sharp rise in a fruit's respiration rate, affecting the stationary oxygen and carbon dioxide levels inside the package. Therefore, knowledge of the evolution of food products throughout the refrigerated storage process is essential and can be gained through experimental procedures and numerical study. Although experimental research is needed in order to identify real conditions and problems, it can be costly and time-consuming. Numerical study is an alternative tool that can be used to reproduce refrigerated storage conditions in order to study the influence of different factors on food product preservation.

Pineapple (*Ananas comosus*) is a non-climacteric fruit appreciated for its flavor, juiciness, texture, and vitamin C and fiber content (Paull and Chen, 2003). However, slicing vegetable tissues leads to an increase in the metabolic process and can result in significant changes in their textural, color and flavor properties (Del Nobile et al., 2009). The shelf life of fresh cut pineapple is closely tied to its packaging conditions and storage temperature (Soliva-Fortuny et al., 2002).

Selling minimally processed fresh fruit requires a combination of intelligent strategies that extend shelf life while maintaining sensory and organoleptic properties. The main factors that determine the success of a fresh cut fruit product include starting with a high-quality raw material and maintaining the cold chain throughout the manufacturing, distribution and marketing processes (Artés et al., 2007). Modified atmosphere packaging and refrigerated storage are frequently used to reduce the respiration rate without negatively affecting the physiology of the fruit and to increase shelf life (Montero-Calderón et al., 2008). The appropriate gas composition depends on the respiration rate of the produce. Mathematical models have been proposed to correlate the respiration rate with different storage parameters such as gas composition and temperature, but the two factors have rarely been considered simultaneously. Although pineapple is the most commonly consumed tropical fruit in the world, the literature contains few references to the respiration rate of pineapple varieties. The respiration rate of pineapple pulp is twice as high as the whole fruit (Marrero and Kader, 2006). Budu and Joyce (2005) found an exponential relationship between the respiration rate of 'Smooth Cayenne' pineapple slices and O_2 and CO_2 concentrations at a fixed temperature. On the other hand, Marrero and Kader (2001) reported that the shelf life of the same pineapple variety ranged from a few hours at 20 °C to over 2 weeks at 0 °C (in a modified atmosphere) indicating that

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Nomenclature

a	regression coefficient
b	regression coefficient
c	regression coefficient
c_p	specific heat, J kg^{-1} K^{-1}
E	mean relative deviation modulus, %
E_a	activation energy, kJ mol^{-1}
K_i	Michaelis–Menten constant for uncompetitive inhibition, %
K_{mO2}	Michaelis–Menten constant for O_2 consumption, %
K_{mCO2}	Michaelis–Menten constant for CO_2 consumption, %
k_p	pineapple thermal conductivity, W m^{-1} K^{-1}
A	quality factor
R	universal gas constant, 8.314 J mol^{-1} K^{-1}
R_{O2}, R_{CO2}	respiration rate (O_2 consumption, and CO_2 production), ml kg^{-1} h^{-1}
R_{O2max}, R_{CO2max}	maximum respiration rate (O_2 consumption, and CO_2 production), ml kg^{-1} h^{-1}
T	storage temperature, °C
T_{abs}	absolute temperature, K
t	storage time, h
$[O_2]$	oxygen concentration, %
$[CO_2]$	carbon dioxide concentration, %
Greek letter ρ_p	density, kg m^{-3}

temperature plays a considerable role in the lifespan of the product. Texture is an important attribute that determines consumers' acceptance or rejection of fresh cut fruits (Soliva-Fortuny et al., 2002). Several authors have studied pineapple texture (Eduardo et al., 2008; Gil et al., 2006; Liu et al., 2007; Martínez-Ferrer and Harper, 2005; Montero-Calderón et al., 2010) but no prior research has examined the effect of different storage temperatures on texture. Inadequate temperatures promote tissue softening and juice leakage; therefore, studying the influence of storage temperature on fruit is useful in predicting pineapple firmness.

The aims of this work were: (a) to develop and validate a heat transfer model for the processed product during air-cooling, (b) to develop and validate a respiration model based on enzyme kinetics and (c) to evaluate the texture of pineapple at different temperatures throughout storage.

2. Materials and methods

2.1. Mathematical procedures

2.1.1. Transient heat transfer model during cooling

The heat transfer model is enforced by setting the balance of energy equation

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot Q = 0 \quad (1)$$

where ρ indicates density (kg m^{-3}), c_p is specific heat (J kg^{-1} K^{-1}), t is time (s), T is temperature (°C), and Q is thermal flux. The heat flux Q is defined by Fourier's law as:

$$Q = -k_p \nabla T \quad (2)$$

where k_p is conductivity (W m^{-1} K^{-1}) and $\nabla T = \left[\frac{\partial T}{\partial x}\ \frac{\partial T}{\partial y}\ \frac{\partial T}{\partial z}\right]$ is temperature gradient.

The following step is the integration of this equation into the entire domain of the problem, Ω. After applying the weighted residual method, the weak form (global equilibrium) of the problem is stated as:

$$\int_\Omega \delta\omega r(T) d\Omega = 0 \quad (3)$$

where $r(T)$ is the residual of the balance equation defined as:

$$r(T) = C_P \frac{dT}{dt} - \nabla Q \quad (4)$$

If the Garlerkin method is applied, the arbitrary weight function $\delta\omega$ can be replaced by δT and the weak form of the balance of energy equation results in:

$$\int_\Omega \delta T C_p \frac{dT}{dt} d\Omega - \int_\Omega \delta T \nabla \cdot Q d\Omega = 0 \quad (5)$$

Integrating the last term in the above expression and taking Fourier's law into account (Eq. (2)), it is possible to write:

$$\int_\Omega \delta T C_{Piña} \frac{dT}{dt} d\Omega + \int_\Omega \nabla(\delta T) K_{Piña} \nabla T d\Omega = \int_\Omega \Gamma_q T \bar{q} d\Gamma \quad (6)$$

where $\bar{q} = Q \cdot n$ is the heat flux (Neumann condition) normal to the boundary of the domain, Γ_q. The Dirichlet boundary condition must be considered in terms of prescribed temperature, $T = \bar{T}$ along the Γ_T boundary. The Neumann boundary condition is also commonly considered in terms of either heat convection or radiation fluxes. Applying Newton's law, heat convection flux can be expressed as:

$$\bar{q}_{conv} = h_{conv}(T - T_{env}) \quad (7)$$

where T is the product surface temperature, T_{env} is the environment temperature and h_{conv} is the heat convection coefficient.

Heat radiation flux can be stated as:

$$\bar{q}_{rad} = \varepsilon \rho_0 (T^4 - T^4_{env}) \quad (8)$$

where ε is the emissivity of the material and ρ_0 is the Boltzmann constant (J K^{-1}).

Finally, when the initial condition is imposed, the thermal problem is totally defined:

$$T(0) = T_o \quad (9)$$

The following assumptions were made:

(a) The food sample is homogeneous and isotropic.
(b) The initial temperature T_0 of the sample is homogeneous.
(c) Heat and mass transport due to moisture surface evaporation is negligible.
(d) The heat generated by respiration of minimally processed pineapple is negligible.
(e) The heat exchange between pineapple and air takes place by natural convection.

The system of unsteady nonlinear partial differential equations was solved by the finite element method (FEM) using the heat transfer module of Profood (CIMNE, Spain). FEM has been successfully used by other authors in the study of food processing and conservation. For example, Itaya et al. (1995) used FEM to model heat and moisture transfer in composite foods during drying, Misra and Young (1979) simulated the cooling of apples, Ngadi et al. (1997) modeled moisture transfer in chicken drumsticks during deep-fat frying, Pan and Bhowmik (1991) analyzed heat transfer in fresh tomatoes during cooling and Wang and Sun (2002) studied the three-dimensional transient heat transfer of roasted meat during air blast cooling.

2.1.2. Respiration model

The respiration rate of fruit tissues refers to a global process that encompasses the diffusion of gases through the tissues as well as respiration at the cellular level (Cameron et al., 1995). Fonseca et al. (2002) reviewed several models that describe the relationship between gas concentrations and the respiration rate of fruit, although enzymatic models have been chosen in many cases (Bhande et al., 2008; Mahajan and Goswami, 2001). Oxygen consumption over time can be expressed using the Michaelis–Menten model

$$R_{O_2} = \frac{R_{O_2\,max}[O_2]}{K_m + [O_2]} \quad (10)$$

where R_{O_2max} is the maximum respiration rate and K_m is the oxygen concentration at which the respiration rate is half of R_{O_2max}. An uncompetitive CO_2 inhibition model (Hagger et al., 1992; Lee and Lee, 1996; Mangaraj and Goswami, 2011; Song et al., 1992) was also fitted to the data to study the possible effect of CO_2 concentration on O_2 consumption:

$$R_{O_2} = \frac{R_{O_2\,max}[O_2]}{K_m + \left(1 + \frac{[CO_2]}{K_{CO_2}}\right)[O_2]} \quad (11)$$

Similar equations can be written for CO_2 production. The determination coefficient (R^2) and the mean relative deviation modulus (E) were calculated to evaluate the accuracy of the model. In general, the lower the modulus, the better the agreement between the experimental and predicted data (Bhande et al., 2008; McLaughlin and O'Beirne, 1999).

2.1.3. Kinetics of fruit deterioration

Several authors have proposed kinetic laws for predicting changes in food quality during processing and storage (Ávila and Silva, 1999; Villota and Hawkes, 1992). In general, the reaction rate expression for the degradation kinetics can be written as follows (Van Boekel, 2008)

$$\frac{dA}{dt} = -kA^n \quad (12)$$

where $A(t)$ is the quantitative value of the texture of the product under consideration, k is the rate constant (time^{-1}), and n is the order of the reaction. The kinetic constant k is dependent on temperature and this relationship can often be expressed by the Arrhenius equation (Purwadaria et al., 1979; Taoukis et al., 1997). Zero-order or first-order models are frequently reported with regard to changes in foods (Chen and Ramaswamy, 2002). For $n = 0$, the relationship between a quality attribute and time is linear; therefore substituting in Eq. (12) yields:

$$A = A_0 - kt \quad (13)$$

2.1.4. Temperature dependence

The influence of storage temperatures on the respiration rate and texture of fresh cut pineapple was estimated using the Arrhenius equation

$$P^{(i)} = P^{(i)}_{ref} exp^{\left(\frac{-E_a}{RT_{abs}}\right)} \quad (14)$$

where $P^{(i)}$ is the parameter value, $P^{(i)}{}_{ref}$ is the pre-exponential factor, R is the gas constant, E_a is the activation energy and T_{abs} is the absolute temperature. The Eq. (14) can be expressed in a linear form as shown in Eq. (15):

$$\ln P^{(i)} = \ln P^{(i)}_{ref} - \frac{E_a}{R}\left[\frac{1}{T_{abs}}\right] \quad (15)$$

2.2. Experimental procedures

2.2.1. Preparation of fresh cut produce

Costa Rican 'Del Monte MD2' type fresh pineapples (*A. comosus*) without crowns were provided by a fresh-cut company (Barcelona, Spain). The fruit was stored at 7 °C until processing. The pineapples were immersed in 200 mg mL^{-1} sodium hypochlorite for 3 min at 15 °C (bath and room temperature were the same) and drained. Slices of one centimeter were obtained with a pineapple peeler. The slices were cut into wedges (8–9 g each) with sharp knives. The fruit pieces were carefully mixed and 90 g of the pineapple wedges were packaged on polypropylene trays (255 ml) with 126.45 cm^2 of gas exchange area. The trays were thermo-sealed using a manual sealer (ILPRA Easybox, Ilpra Systems, Italy) with a PET-PP-EVOH-PP film (P_{O2}, P_{CO2} < 1 ml m^2 d^{-1}bar^{-1}, thickness 0.85 mm) and kept at 4, 7 and 13 C for up to 10 days. Initial total solid soluble content and titratable acidity (citric acid) were 12–14 °Brix and 1–1.3 g 100 g^{-1}, respectively.

2.2.2. Temperature measurement

To acquire experimental data and to validate the heat transfer model, different experiments were performed using minimally processed pineapple packaged on polypropylene trays. Five copper-constantan thermocouples (TC Direct, Spain) were used to measure both the temperature evolution of the pineapple wedges at the cold point and the ambient temperature. The thermocouples were distributed as follows: one registered the air temperature inside the tray, another monitored the ambient temperature (cooling chamber) and the remaining devices were inserted in the fruit. The thermocouples were inserted at different positions and covered the entire area of the pineapple wedges. After calibration, the temperature readings were accurate within 0.2 °C and the sampling period was set at 5 s. Each experiment was replicated twice. Predicted and experimental data were compared by calculating the root mean square error (RMSE) as suggested by Iezzi et al. (2011).

2.2.3. Respiration measurement

The respiration rates of pineapple wedges were measured using a closed system method (Hong and Kim, 2001; Lee et al., 1994; Yam et al., 1993). Approximately 200 g of pineapple was placed in 997 ml airtight glass jars containing air as the initial gas atmosphere. The jars were simply closed with metal caps equipped with silicone septums when the target temperature was reached. Sampling of the headspace gas concentrations was terminated when the level of CO_2 inside the jars reached approximately 20%, as the enzymatic model is valid only for aerobic respiration. Headspace O_2 and CO_2 gas concentrations in individual jars were monitored using a Checkmate II gas analyzer (PBI Dansensor, Denmark). Gas samples were taken by inserting a needle through the septum attached to the lid of the jars. Gas readings were taken continuously until stable data were displayed on the screen. To avoid modifications in the headspace gas composition and pressure due to gas sampling, a return needle was also attached to the septum. Typically, the samples were taken every hour for the first six hours, then every nine hours and finally every day. Changes in O_2 and CO_2 concentrations were used to estimate respiration rates according to Eqs. (10) and (11). Experiments were conducted at 2, 4, 7 and 13 °C and the determinations at each temperature were conducted in quadruplicate. The free volume of the jars (Table 1) consisted of the total volume of the jars minus the volume occupied by their content, calculated as a function of the product mass and density (ρ_p). The density was calculated following the method of Choi and Okos (1986) as reported in Section 3.1.

Table 1
Free volume and weight of pineapple taken for generating the respiration rate[a].

T (°C)	Weight of pineapple (kg)	Free volume (ml)
2	0.202 ± 0.001	802.98 ± 1.54
4	0.200 ± 0.003	804.73 ± 1.81
7	0.201 ± 0.001	804.08 ± 1.86
13	0.198 ± 0.004	806.56 ± 3.46

[a] Values are average of four replicates.

2.2.4. Texture measurement

A minimally processed pineapple texture analysis was performed using a TA.XT2 texture analyzer (Stable Micro Systems, UK) with a 30 kg load cell. Firmness was measured as the work required to depress 4 mm into the fruit with a 2 mm flat head stainless steel cylindrical probe at a speed of 1 mm min^{-1} with automatic return. The work was calculated as the area under the curve until the maximum force recorded in the force–displacement curve. Nine replicates were carried out at 4, 7 and 13 °C. Statistical differences were examined by two-way analysis of variance (ANOVA) follow by a Tukey's HSD (Honestly Significant Difference) test to compare means at a significance level of 5%.

3. Results and discussion

3.1. Heat transfer model

In the FEM analysis, the domains were defined by three volumes: the food, the tray and the surrounding air. First, the geometry of the system was discretized with a non-structured mesh made up of 53,043 tetrahedral elements and 10,165 nodes. For all simulations, the problem was solved by a linear system solver and the time step was set to 150 s. The experimental procedures in the cooling chamber were conducted under low air circulation, therefore natural convection can be assumed. The heat transfer coefficient used to calculate the heat convection flux was h_{conv} = 24.5 W m^{-2} K^{-1} and radiation flux was disregarded. Fig. 1a shows the model for the pineapples wedges inside the thermo-sealed polypropylene trays and the mesh used to describe the domain. The analysis was performed starting from a uniform temperature throughout the system (14.8 °C) and continuing until it reached the temperature of the cooling chamber (6 °C). The cooling chamber temperature was constant and the cooling cycles were disregarded. The thermal properties $\rho_p(T)$, $c_p(T)$, and $k_p(T)$ used in the simulation were calculated from the formulation proposed by Choi and Okos (1986). For this propose, the composition of pineapple was assumed as: water 85.75%, carbohydrates 14.29%, protein 0.47%, minerals 0.3%, fiber 0.45% and fat 0.04%, as previously published by Chaiwanichsiri et al. (1996). The average values used were ρ_p = 1044.32 kg m^{-3}, c_p = 3825.48 J kg^{-1} K^{-1} and k_p = 0.5464 W m^{-1} K^{-1} and were considered independent of temperature in the range 0–20 °C because no phase change occurred.

Fig. 1b shows the temperature distribution after one hour of air-cooling and Fig. 2 shows the predicted and experimental time evolution temperatures at the center and at a border point of the pineapple wedges for the air-cooling experiments. These results show us that the pineapples wedges reached the same equilibrium temperature in 3 h in both places measured: at the surface and at the center of the wedge, indicating a complete homogeneous temperature distribution inside the pineapple piece after this time. The difference between the typically storage time (days) and the time that the pineapple wedges need to arrive to the equilibrium temperature (3 h) guarantees that both the respiration and texture measurements are made under steady state conditions.

As shown, the numerical model satisfactorily predicts the temperature evolution of the air cooling process. As expected, the surfaces of the wedges exposed directly to the air have a faster heat exchange rate. The trays of pineapple wedges reached the equilibrium temperature after 3 h of refrigerated storage.

3.2. Respiration rate

The instantaneous respiration rate can be obtained by plotting the gas concentrations inside the jars versus time, but this method is not recommended due to the wide variations in many experimental data. Instead, a regression function is often used to fit the data of gas concentrations only as a function of time (Gong and Corey, 1994; Hagger et al., 1992; Jacxsens et al., 1999). Fig. 3 shows the O_2 and CO_2 concentrations inside the closed jars as a function of time. These experimental values were fitted by a second order polynomial function:

$$[O_2(t)] = at^2 + bt + c \tag{16}$$

$$[CO_2(t)] = a't^2 + b't^2 + c' \tag{17}$$

The a, b and c values for O_2 consumption and CO_2 production are given in Table 2. The derivatives of Eqs. (16) and (17) were used to calculate the respiration rates following the three step method proposed by Gong and Corey (1994). The respiration rate can be expressed as only a function of gas concentrations:

$$R_{O_2} = 10\sqrt{b^2 - 4a(c - [O_2])}W^{-1}V \tag{18}$$

$$R_{CO_2} = 10\sqrt{b'^2 - 4a'(c' - [CO_2])}W^{-1}V \tag{19}$$

Next, the experimental respiration rates obtained from Eqs. (18) and (19) were used to estimate the model parameters of Eq. (10) by means of nonlinear regression with the Levenberg–Marquardt algorithm using MATLAB software ver. 7.11 (Matworks Inc., USA).

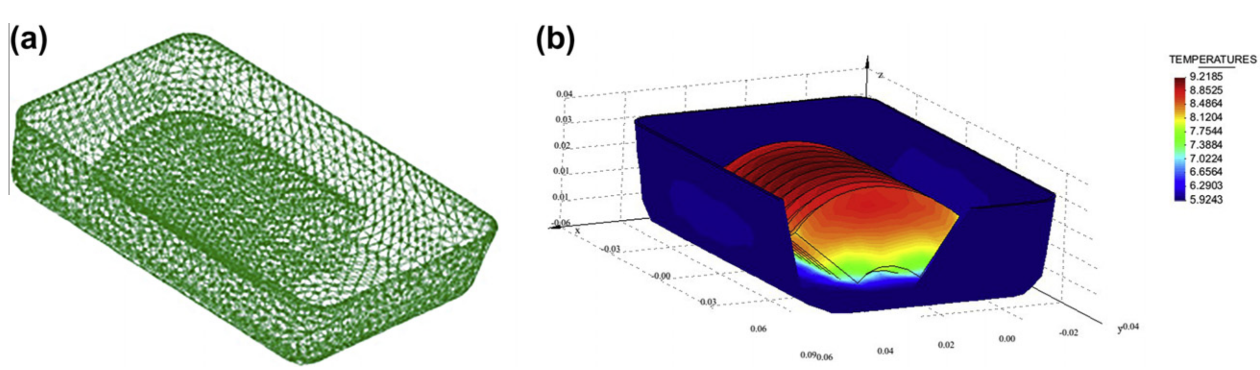

Fig. 1. (a) Geometry and resulting mesh for minimally processed pineapple on polypropylene trays and (b) temperature distribution on pineapple wedges after one hour in the cooling chamber.

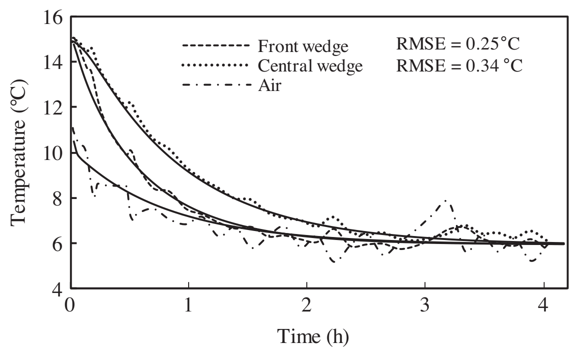

Fig. 2. Experimental and predicted temperatures during the cooling process on the front wedge point (0, 0.02, 0.006) and on the central wedge point (0, −0.02, 0.02). Coordinates are expressed in meters. The continuous lines represent the FEM simulations.

Table 3
Michaelis–Menten R_{max} and K_m coefficients (95% confidence interval).

T (°C)	R_{O2max} (ml O_2 kg^{-1} h^{-1})	K_{mO2} (%)	E (%)	R^2
2	4.59 ± 0.06	17.78 ± 0.50	0.10	0.99
4	4.81 ± 0.12	16.27 ± 0.80	1.26	0.99
7	7.61 ± 0.39	12.88 ± 1.43	0.99	0.99
13	16.71 ± 1.15	12.28 ± 2.04	0.04	0.99
T (°C)	R_{CO2max} (ml CO_2 kg^{-1} h^{-1})	K_{mCO2} (%)	E (%)	R^2
2	3.40 ± 0.77	2.98 ± 1.54	14.04	0.93
4	4.15 ± 0.70	3.71 ± 1.53	10.24	0.93
7	12.40 ± 1.67	9.70 ± 2.82	13.37	0.98
13	29.93 ± 4.74	8.53 ± 2.77	15.97	0.98

Table 3 presents the values of the model parameters at each temperature. The excellent agreement between the predicted and experimental data verifies the goodness of the model parameters (R^2 > 0.93). The possible inhibiting effect of CO_2 on O_2 uptake was studied through Eq. (11). In these studies, the inclusion of parameter K_i did not improve the fit of the respiration rates and the confidence intervals were quite high (data not shown). The O_2 consumption of about 2.4 ml kg^{-1} h^{-1} at 4 °C and 10% O_2 (Fig. 4a) is close to the 2.5–3 ml kg^{-1} h^{-1} at 4.5 °C reported for 'Smooth Cayenne' pineapple slices by Budu and Joyce (2005). Average respiratory quotients (RQ = R_{CO2}/R_{O2}) for aerobic respiration ranged between 0.7 and 1.06 depending on the storage temperature and increased as O_2 concentration decreased. The RQ depended on both O_2 concentration and temperature (Talasila et al., 1992).

Dependence on temperature as estimated by the Arrhenius equation (Eq. (15)) was determined by plotting the natural logarithm of the model parameters against the inverse of temperature. The resulting linear plot for each parameter is shown in Fig. 4b. Temperature had a significant effect on respiration rate as Marrero and Kader (2006) have reported in previous studies. Activation energy was calculated from the slope of the line and the pre-exponential factor was calculated from the Y-axis intercept. Table 4 shows the activation energy and pre-exponential factors for different model parameters of enzyme kinetics. Activation energy values range from 29 to 93 kJ mol^{-1} for fruits and vegetables (Exama et al., 1993) but can be as high as 136 kJ mol^{-1} (Jacxsens et al., 2000). If we consider that a passive atmosphere modification take place in the pineapple trays it means that the O_2 concentration at time zero is 20.8%. Taking into account the temperature evolution profile of the pineapple wedges (Fig. 2) coupled to the Michaelis–Menten respiration model, we estimate that in the first three hours of cooling at least a 1.7% of O_2 is consumed.

Model predicted respiration rates of pineapple were verified with experimental respiration rates at 15 °C. This temperature was chosen as it is the average temperature of the acclimated processing room. The a, b and c constants obtained for Eqs. (16) and (17) were 0.001, −0.2863, 19. 97 for O_2 consumption and 0.004, 0.1934 and 2.32 for CO_2 production with an R^2 of 0.98 and 0.91, respectively. The free volume of the jars and the weight of the pineapple taken for verification were 803.67 ml and 202.02 g, respectively. The experimental respiration rates of the pineapple at 15 °C were determined using the method proposed by Gong and Corey (1994) and the predicted respiration rates were calculated with the model parameters gave in Table 4. The mean relative modulus and correlation coefficients were 3.86% and R^2 > 0.997 for R_{O2} and 18.34% and R^2 > 0.992 for R_{CO2}, thus confirming the predictive ability of the model (E < 20%).

3.3. Texture

Firmness measurements (N mm) were taken as the area under the curve from 0 to maximum force in the puncture test. Two-way ANOVA showed significant effects of both temperature and storage time, with no cross effect (Table 5). Fig. 5 shows the firmness

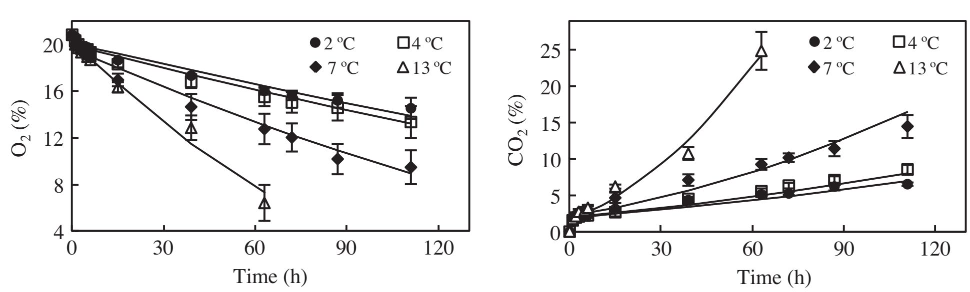

Fig. 3. Changes in gas concentrations inside closed jars containing cut pineapple.

Table 2
Values of coefficients for experimental O_2 consumption and CO_2 production.

T (°C)	a O_2	b O_2	c O_2	R^2	a' CO_2	b' CO_2	c' CO_2	R^2
2	4.74E−05	−6.16E−02	20.11	0.962	1.01E−04	3.42E−02	1.92	0.864
4	5.55E−05	−6.62E−02	19.91	0.986	1.45E−04	3.80E−02	2.04	0.974
7	1.71E−04	−1.16E−01	19.67	0.982	5.47E−04	6.82E−02	2.14	0.979
13	8.23E−04	−2.59E−01	20.34	0.980	3.29E−03	1.51E−01	1.72	0.949

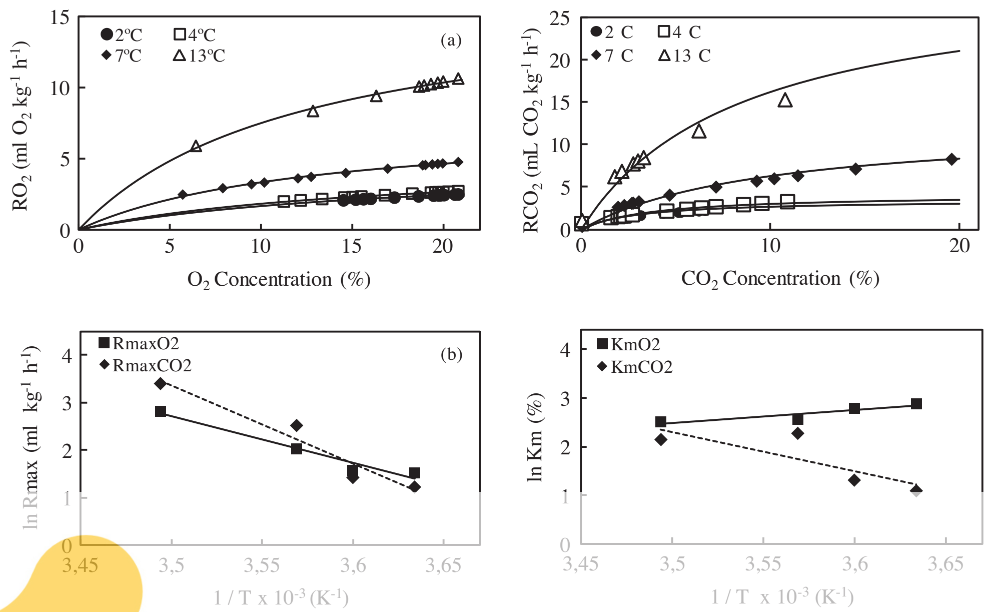

Fig. 4. (a) Effect of gas concentrations and temperature on the respiration rate fit with a Michaelis–Menten model (continuous lines) and (b) Arrhenius relation for model parameters of enzyme kinetics.

Table 4
Activation energy and pre-exponential factors of Arrhenius type equation for the model parameters.

	E_a (kJ mol^{-1})		$P_{ref}^{(i)}$		R^2	
	O_2	CO_2	O_2	CO_2	O_2	CO_2
R_{max}	80.87	135.83	9.57E15	2.08E26	0.98	0.96
K_m	−22.38	65.75	9.60E−4	1.06E13	0.83	0.67

Table 6
Kinetics parameters of texture loss.

T (°C)	Q_o	k (min^{-1})	R^2
4	3.79	2.04 E-1	0.96
7	3.50	1.85E-1	0.86
13	3.24	1.74E-1	0.65

Table 5
F-values obtained in the two-way ANOVA of the pineapple firmness.

Factor	F
Temperature (4, 7 or 13 °C)	10.443*
Storage time (2, 4, 6, 8 or 10 days)	6.661*
Temperature × time	1.148

* Significance level: $p < 0.05$.

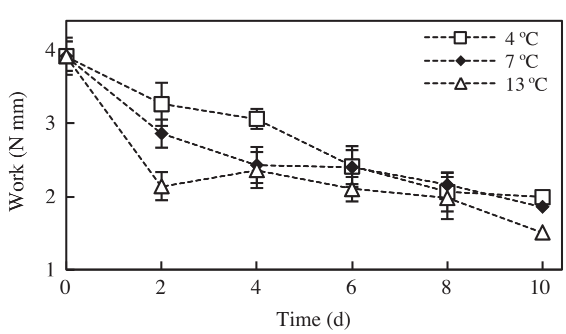

Fig. 5. Firmness of pineapple wedges over 10 days of storage at different temperatures. Vertical bars represent the mean standard error.

decrease during storage. At days 2 and 4, firmness of pineapple wedges stored at 4 °C was superior compared to the wedges stored at 7 and 13 °C ($p < 0.05$). This texture loss is due to a decrease in cell wall turgor or to the enzymatic activity on the cell wall constituents. The temperature dependence of the kinetic constants was calculated using the Arrhenius equation. The zero-order reaction rate constants (Table 6) followed an Arrhenius-type equation, yielding a coefficient of determination value of 0.925. The activation energy and pre-exponential factor were determined as −9.55 kJ/mol and 3.13E−3, respectively. The negative activation energy value implies that the texture varied negatively as temperature increased.

4. Conclusions

The FEM was satisfactorily applied to solve the fruit-tray-environment scheme for heat exchange. The comparison between predicted and measured temperatures demonstrated the consistency of the model to correctly predict heat transfer (RMSE < 0.34 °C) during natural convective air-cooling. The proposed FEM heat model can help to estimate the benefits of other packaging alternatives (e.g. using a thermal insulation layer) and can generate curves for temperature evolution as a function of package characteristics (size and selected material) for a given minimally processed product. The oxygen consumption and carbon dioxide production at different temperatures can be accurately predicted through Michaelis–Menten kinetics without inhibition by CO_2. Finally, the textural degradation of pineapple wedges followed zero-order kinetics and the temperature relationship was estimated using the Arrhenius equation, as well the enzymatic parameters of respiration rates.

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